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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE – Radiation Intensity Due to Co^{60} Radioactive Fuel Gauges

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DATE – June 10, 1966

AUTHOR(S) – T. C. Tweedie, Jr.

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Spacecraft Radiation
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ABSTRACT

Experiments mounted on the Apollo spacecraft may be adversely affected by the radiation emitted from the Co^{60} used in the RCS fuel gauging system. To assist in proper placement of radiation sensitive experiments a quantitative estimate of the radiation intensity in the free volume of Sector I of the service module and at the LEM Descent Stage is made. This estimate should be regarded as approximate since it is based on a simplified model which is fully described in the text of this memorandum. Two cases are examined:

1. RCS radiation gauges installed on both SM and LEM

2. RCS radiation gauges installed on SM only; LEM gauges removed.

Based on the limited model assumed for the distribution of the SM radiation sources and the radiation attenuation by the spacecraft, the LEM Descent Stage is a more favorable location for installation of radiation sensitive experiments than Sector I of the Service Module. Removal of the LEM Co^{60} RCS gauges substantially reduces the photon flux at the bottom of the Descent Stage.

Finally it should be stressed that particular experiments must be considered individually with regard to their sensitivity to X-ray radiation and to their precise location on the spacecraft since the possibilities of "windows" cannot be neglected.

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FROM: T. C. Tweedie, Jr.

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TECHNICAL MEMORANDUM

Introduction

Implementing the suggestion of the National Academy of Sciences as stated in the report of the Woods Hole Meeting 1965 to assign a priority for X-ray and gamma-ray astronomy comparable to that of optical or radio astronomy, NASA/OSSA has proposed a tentative grouping of X-ray and gamma-ray sensors for early Saturn Apollo Applications Program (SAA) missions. On these early missions broad surveys in the short wavelengths of interest are planned to provide basic knowledge of the directional and spectral characteristics of the deep space radiation sources. Since the Earth's atmosphere strongly absorbs short wavelengths, the X-ray or gamma-ray sensors would be mounted on Earth-orbiting manned Apollo spacecraft which can support the experiments for approximately 14 days. This duration represents several orders of magnitude improvement over previous experiments performed on unmanned rocket flights. Unfortunately the Apollo spacecraft, both CSM and LEM, contains radioactive isotopes used in the reaction control system (RCS) fuel gauges. The radiation emitted by these gauges is sufficient to affect adversely many experiment sensors and in some cases to obliterate completely the low signal strength expected from the celestial sources.

If the X-ray or gamma-ray sensors are mounted in the Service Module, radioactive RCS gauges interfere with the experiment detectors; if the sensors are mounted on the LEM, similar radioactive gauges also compromise experiment sensitivity. It has been proposed that the LEM RCS gauges (located in the Ascent Stage) be removed, and that the radiation sensitive experiments be mounted on the bottom of the Descent Stage. Since the LEM RCS gauges are not needed for crew safety on Earth orbital missions (the SM RCS is needed during retrofire and for SM/CM separation), removal of the isotopes in the LEM gauging system is a possible solution to the radiation background problem.

The radiation levels in the free volume of Sector I of the Service Module and at the LEM Descent Stage are determined and compared for two cases:

1. RCS radiation gauges installed on both SM and LEM,

2. RCS radiation gauges installed on SM only; LEM gauges removed.

Radiation Sources

The fuel gauging system on the RCS tanks relates the amount of fuel present in a tank to the attenuation of the photons emitted by a known amount of the radioactive isotope Co^{60} mounted around the tank. In the SM there are eight RCS tanks distributed symmetrically in pairs in a plane normal to the spacecraft principal axis. On each tank there are 3.12 millicuries of Co^{60} for a total of 24.96 millicuries. In the LEM Ascent Stage there are four RCS tanks also containing 3.12 millicuries of Co^{60} for a total source strength of 12.48 millicuries. These tanks are also located symmetrically about the principal axis.

Cobalt 60 in its principal decay scheme to Nickel 60 emits one beta ray and 2 photons.[1] The prominent features of the decay scheme are shown in Figure 2. The decay of Co^{60} by emission directly to the Ni^{60} ground state is negligible (less than 1 in 10^6); the number of transitions from Co^{60} to Ni^{60} at the 1.33 Mev level is only about 0.3% of the transitions to the 2.50 Mev level. Thus for all practical purposes the decay of Co^{60} to Ni^{60} is characterized by single beta emission to the 2.50 Mev level of Ni^{60} followed by the emission of two photons with energies of 1.17 Mev and 1.33 Mev.

Shielding Models

While the radiation level at the Descent Stage location is best determined experimentally, reasonable values of the radiation intensity can be calculated by assuming simple models for the position of the radiation sources, and the geometry of the spacecraft. The simplest model assumes that all the distributed radiation sources in the SM fuel gauges are concentrated at a point on the axis of symmetry and that there is no attenuation of the radiation by the structure. Thus the radiation at any given point is equal to the original source strength reduced by the $4\pi R^2$ areal dependence.

To calculate the effect of the radiation sources as they are distributed in the RCS fuel tanks and of the attenuation by the structure, a more complicated model is used. The cobalt radiation sources in the SM RCS tanks are assumed to act as a plane source with the total radiation intensity distributed uniformly over a disc which matches the cross section of the service module. This assumption is consistent with the actual location of the SM tanks relative to the LEM Descent Stage (Figure 1). If the 24.96 millicuries are distributed over a 13 ft. diameter disc (SM diameter), a plane intensity source of 2×10^{-7} curies/cm^2 is obtained.

Since the CM and LEM are hollow irregularly shaped structures, partially filled with equipment, the path length of the radiation in the materials used in calculating the attenuation cannot be easily determined. To approximate the path length, each structure is assumed to be completely compressed into a solid right circular cylinder whose cross section matches that of the plane radiation source. The height of the cylinder is now the equivalent thickness or layer of the particular module.

The intensity of radiation I after passing through the equivalent layers of shielding can now be calculated by the simple exponential decay form $e^{-\mu x}$, where μ is the linear absorption coefficient of an individual layer, x is the equivalent thickness of the layer, and I_o is the incident intensity. The equation relating these parameters is

$$I=I_o e^{-\mu x}$$

The linear absorption coefficient, or fractional decrease in intensity of radiation per unit thickness of absorber, depends on both the energy of the photons being attenuated and the materials used. In general, there are three mechanisms for intensity reduction: Compton scattering, photoelectric effect, and pair production. The sum of the three mechanisms, each of which is energy dependent, is the linear absorption coefficient.

At the average energy of the two Co^{60} photons, 1.25 Mev., Compton scattering is the primary contribution to the absorption coefficient.[2] The coefficient of the various materials, obtained from published data, is shown in Table I.

Radiation at LEM Descent Stage Due to SM Gauges Only

Using the average energy of the two emitted photons and the procedure outlined below, the equivalent layers and the fractional radiation intensity I/I_o are calculated. The results are tabulated below. The density and mass absorption coefficients for the various materials considered are also shown in Table I.

The weight of each structure is divided by the density of its material; the resulting volume is now distributed as a right circular cylinder by dividing by the cross sectional area of the SM and hence matching the previously assumed plane radioactive source (Figure 2). In calculating the equivalent layer thickness of the structures and fuel, each item is assumed to be made completely of a single material. Three materials, aluminum, iron and lead, are considered separately as the constituant of the structure to bound the possible variations in materials. A similar procedure is followed for the LEM propellant except that the total propellant weight is divided between two different materials to reflect the variation in weight between oxidizer and fuel.

COMMAND MODULE (CM) - Weight - 11,000 lbs

	Al	Fe	Pb
Equivalent Volume ($ft.^3$)	65	22.5	15.5
Equivalent Length (cm)	15	5.15	3.5
I/I_o	0.102	0.112	0.095

LUNAR EXCURSION MODULE (LEM) - Weight - 10,300 lbs

	Al	Fe	Pb
Equivalent Volume (ft.^{3})	61	21	14.5
Equivalent Length (cm)	14	4.83	3.35
I/I_o	0.119	0.129	0.105

LEM Propellant 17,300 lbs Descent
5,000 lbs Ascent

22,300 lbs

The total weight of propellant is assumed for calculations to be apportioned 66 2/3% oxidizer - 33 1/3% fuel.

	Oxidizer	Fuel
Equivalent Volume (ft^3)	165	132
Equivalent Length (cm)	37	30.4
I/I_o	0.042	0.19

The total fractional intensity is the product of the transmitted intensity from each layer:

$$\left.\frac{I}{I_o}\right|_{\text{Total}} = \left.\frac{I}{I_o}\right|_{\substack{\text{CM}\\ \text{Structure}}} \times \left.\frac{I}{I_o}\right|_{\substack{\text{LEM}\\ \text{Structure}}} \times \left.\frac{I}{I_o}\right|_{\text{Fuel}} \times \left.\frac{I}{I_o}\right|_{\text{Oxidizer}}$$

	Al Structure & LEM Propellant	Fe Structure & LEM Propellant	Pb Structure & LEM Propellant
$\frac{I}{I_o}$ Total	9.75×10^{-5}	11.6×10^{-5}	8.0×10^{-5}

Multiplying the source strength by the calculated total fractional intensity yields the intensity at the end of the equivalent layers, corresponding to the intensity at the bottom of the Descent Stage.

As noted above, a plane source of Co^{60} of 2×10^{-7} curies/cm^2 is assumed to be the origin of the radiation. The plane source value is divided by two (accounting for the directional effect of the source). This reduction is balanced by the emission of two photons in the disintegration of Co^{60} to Ni^{60}.

Thus the source strength is

$$I_o = 2 \times 10^{-7} \frac{\text{curies}}{\text{cm}^2} \times 3.7 \times 10^{10} \frac{\text{disintegrations}}{\text{sec curie}} \times \frac{2 \text{ photons}}{\text{disintegrations}} \times \frac{1}{2}$$

$$I_o = 7.4 \times 10^3 \frac{\text{photons}}{\text{cm}^2 \text{ sec}}$$

Hence the intensity at the far end of the equivalent layers is

	Al + Propellant	Fe + Propellant	Pb + Propellant
$I \left| \frac{\text{photons}}{\text{cm}^2 \text{ sec}} \right.$ Total	0.7	0.8	0.6

If the radiation is not a narrow beam or the attenuating material is thick, then an additional multiplicative term called build-up factor must be included in the intensity calculations. Both of these exceptions are pertinent to the case considered. Based on the materials considered and their equivalent thickness the intensity must be increased by about three to four. The expected photon flux range at the bottom of the descent stage based on the equivalent layer model plus build-up is now

$$2\text{-}3 \ \frac{\text{photons}}{\text{sec cm}^2}$$

If the LEM ascent and descent propellant is not loaded on the LEM (quite probable on earth orbit missions not requiring LEM propulsion), then because of the reduced shielding, the intensity at the descent stage is about 100 times higher, or

$$200\text{-}300 \ \frac{\text{photons}}{\text{sec cm}^2}.$$

For comparison, the above results are tabulated together with the results from the simple I/R^2 areal dependence model (no shielding).

	Structure & Propellant	Structure Only	I/R^2
Flux $\frac{\text{photons}}{\text{sec cm}^2}$	2 - 3	200 - 300	500 - 600

Radiation At Service Module Sector I Due To SM Gauges Only

Sector I of the service module, a 50° pie-shaped empty volume about thirteen feet long, is a possible location in which to install experiments. The proximity of Sector I to the radiation sources, Figure I, causes a high radiation level in Sector I. The radiation level is determined from a simple I/R^2 reduction in source strength between an assumed point source of radiation in each of the eight RCS tanks and the location of interest. The radiation level is calculated at three points in Sector I which lie on a line parallel to the service module's principal axis and four feet from it. This line passes through the approximate center of Sector I. Using the previously stated source strength of 3.12 millicuries of Co^{60} per RCS tank the radiation flux at representative points in the free volume of Sector I are tabulated.

	Distance measured from CM-SM juncture 0 ft.	6.5 ft.	13 ft.
Flux $\frac{\text{photons}}{\text{sec cm}^2}$	3.8×10^3	6.5×10^3	1.5×10^3

Comparing these results for Sector I with those from the previous section, it is noted that the radiation level at the descent stage with no LEM propellant for shielding is one order of magnitude lower than the minimum radiation in Sector I. Under the more favorable shielding condition with fuel in the LEM the radiation level is three orders of magnitude less than that in Sector I.

Radiation Due to LEM Gauges Only

Calculations of the radiation level at the Descent Stage and in Sector I due only to the LEM gauges are summarized. With the symmetric location of the RCS gauges in the LEM and the intervening structure between the radiation sources and the regions of interest, calculation of the radiation level reduces to the problem previously considered of an equivalent layer thickness between a plane radiation source and a region of interest. As was done previously, the I/R^2 radiation reduction is also shown for comparison.

	LEM D/S	Structure	I/R^2
Flux	$\frac{\text{photons}}{\text{cm}^2 \text{ sec}}$	370	600
	Sector I		
Flux	$\frac{\text{photons}}{\text{cm}^2 \text{ sec}}$	50	125

Conclusions

Based on the limited model assumed for the distribution of the SM radiation sources and the radiation attenuation by the spacecraft, the LEM Descent Stage is a more favorable location for installation of radiation sensitive experiments then Sector I of the Service Module. Removal of the LEM Co^{60} RCS gauges substantially reduces the photon flux at the bottom of the Descent Stage.

Finally it should be stressed that particular experiments must be considered individually with regard to their sensitivity to x - ray radiation and to their precise location on the spacecraft since the possibilities of "windows" cannot be neglected.

T. C. Tweedie Jr.

1013-TCT-bhh T. C. Tweedie, Jr.

Attachments
- Table 1
- Figures 1 and 2
- References

TABLE I

	ρ gm/cc	α cm^2/gm*	μ cm^{-1}
Al	2.7	0.0556	0.152
Fe	7.87	0.0540	0.425
Pb	11.34	0.0590	0.673
N_2O_4 (Oxidizer)	1.45	0.06**	0.086
50% Hydrazine 50% UDMH (Fuel)	0.90	0.06**	0.055

* For 1.25 Mev photon

** The mass absorption coefficient is generally a constant for most materials for photons of a particular energy. A nominal value was assumed.

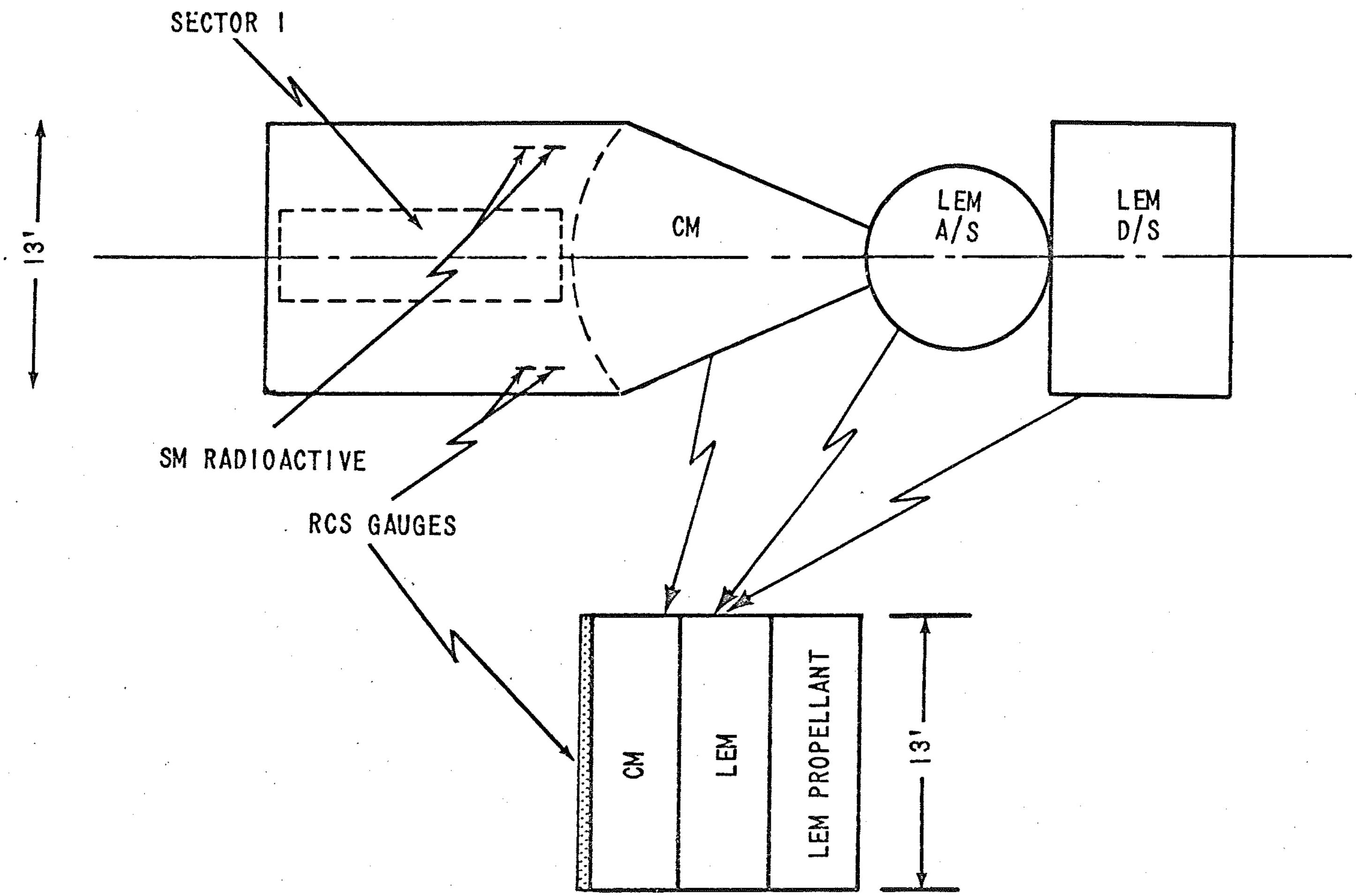

FIGURE I - EQUIVALENT LAYERS USED IN SHIELDING CALCULATIONS

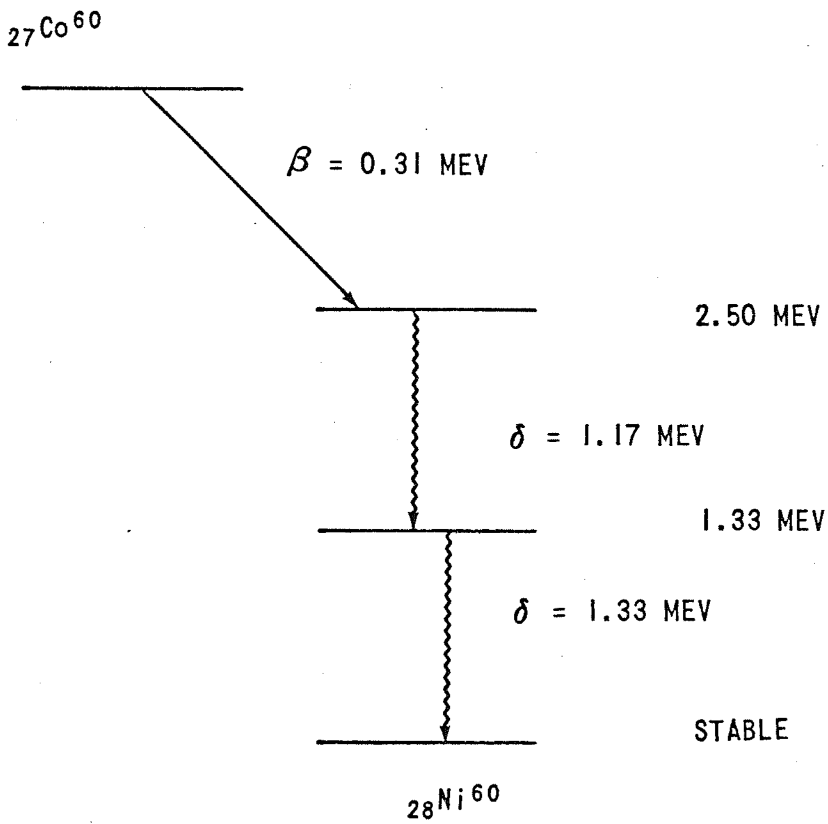

FIGURE 2 - PRINCIPAL DECAY SCHEME OF Co^{60} TO Ni^{60}